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A NEW FERROELECTRIC VARACTOR SHUNT SWITCH FOR MICROWAVE AND MILLIMETERWAVE RECONFIGURABLE CIRCUITS

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14. ABSTRACT
This paper presents a ferroelectric varactor shunt switch which can be useful for microwave/millimeterwave switching as well as for the design of reconfigurable circuits. The device operation is based on nonlinear dielectric tunability of a ferroelectric thin-film sandwiched between two metal layers in the parallel plate configuration. A CPW based design allows for MMIC compatible shunt switches with low insertion loss and high isolation. Experimental performance of the varactor shunt switch indicates good switching performance with ~24 dB isolation @41 GHz, and insertion loss below 7 dB up to 45 GHz.

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A New Ferroelectric Varactor Shunt Switch for Microwave and Millimeterwave Reconfigurable Circuits

Abstract

This paper presents a ferroelectric varactor shunt switch which can be useful for microwave/millimeterwave switching as well as for the design of reconfigurable circuits. The device operation is based on nonlinear dielectric tunability of a ferroelectric thin-film sandwiched between two metal layers in the parallel plate configuration. A CPW based design allows for MMIC compatible shunt switches with low insertion loss and high isolation. Experimental performance of the varactor shunt switch indicates good switching performance with ~24 dB isolation @41 GHz, and insertion loss below 7 dB up to 45 GHz.

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1. Introduction

Micro-electromechanical system (MEMS) switches, semiconductor PIN and/or varactor diodes, and semiconductor based transistors are some of the potential technologies that can be used for tunable/reconfigurable circuits. In comparison with these technologies, ferroelectric devices are fast, small, lightweight, and have low power consumption [1]. Ferroelectric components are simple in nature and allow cost effective integration in complex microwave systems [1-2]. MEMS varactors/switches are possible competitors to ferroelectrics, including frequencies above 10–20 GHz [3-4]. Nevertheless, they are characterized by small tuning speeds (> 10 μs) and complex structure in comparison with ferroelectric varactors. Semiconductor varactors are good competitors to ferroelectric varactors in frequency bands below 10 GHz. Above 10 GHz, the quality factor of semiconductors drastically degrades, while varactors based on ferroelectrics have constant quality factor throughout millimeterwave frequencies [5]. At present, tunable microwave devices based on ferroelectrics are widely being considered for tunable/reconfigurable circuits such as phase shifters, filters and VCOs [6-7]. In this paper, we present a new varactor shunt switch based on Barium Strontium Titanate ($Ba_{0.6}Sr_{0.4}TiO_3$) henceforth BST(60/40) ferroelectric thin-films, for Si MMIC compatible reconfigurable circuits.

2. Ferroelectric Varactor Shunt Switches

The design of the ferroelectric varactor shunt switch has been reported previously [8,9]. Briefly, the varactor shunt switch consists of a CPW transmission line loaded by a ferroelectric varactor in the middle (as shown in figure 1), such that the large capacitance of the varactor at zero bias will shunt the input signal to ground, thus isolating the output port, resulting in the OFF state of the device. When one applies a bias voltage corresponding to a dc field of ~250 kV/cm, (approximately 10 V), the varactor's capacitance is reduced to a minimum, thus allowing most of the signal from the input to get through to the output, thus resulting in the ON state of the device. For the experimental demonstration of the device, a high resistivity Si substrate (~ 6 kΩ cm) with a 300 nm thick SiO2 layer was used.

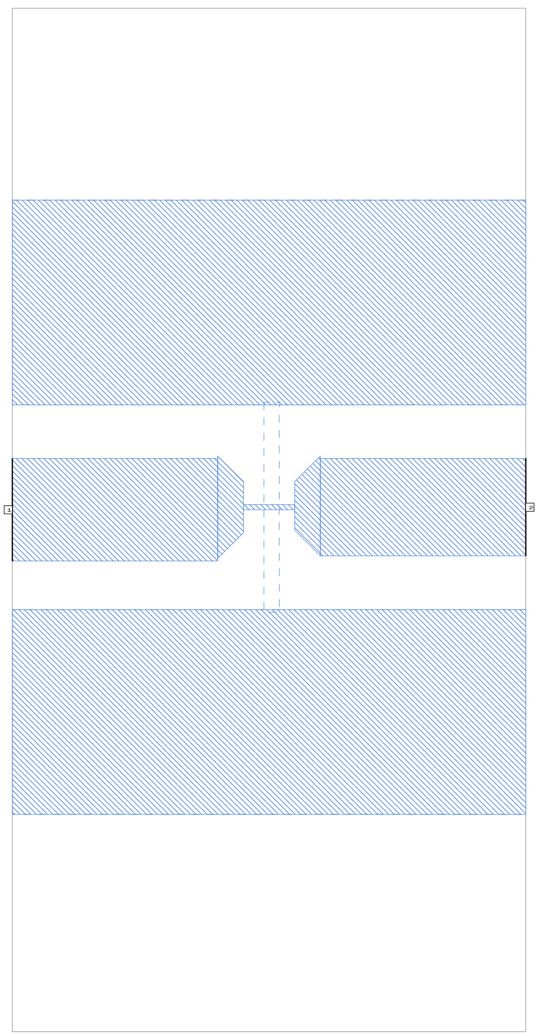

Figure 1. Ferroelectric Varactor Shunt Switch Layout Showing the Plan View

NOTE: The overlap area for the device shown is 5 x 15 μm^2. The meta1l is shown in dotted lines. The overlap area of the metal1 and metal2 defines the varactor area.

The process steps used for the fabrication of the device are shown in figure 2. The processing consists of metal1 layer lithography (10 nm Ti + 800 nm Au + 100 nm Pt), followed by deposition of the BST (60/40) thin-film ~400 nm thick on the entire area, and then the metal2 lithography (10 nm Ti + 1 μm Au). The BST thin-film was deposited using a process controlled pulsed laser deposition (PLD) system, for obtaining nano-structured BST thin-films with low microwave loss and large dielectric tunability [10]. The BST film used in this study was deposited at 75 mT oxygen partial pressure, resulting in an average grain size of 60 nm.

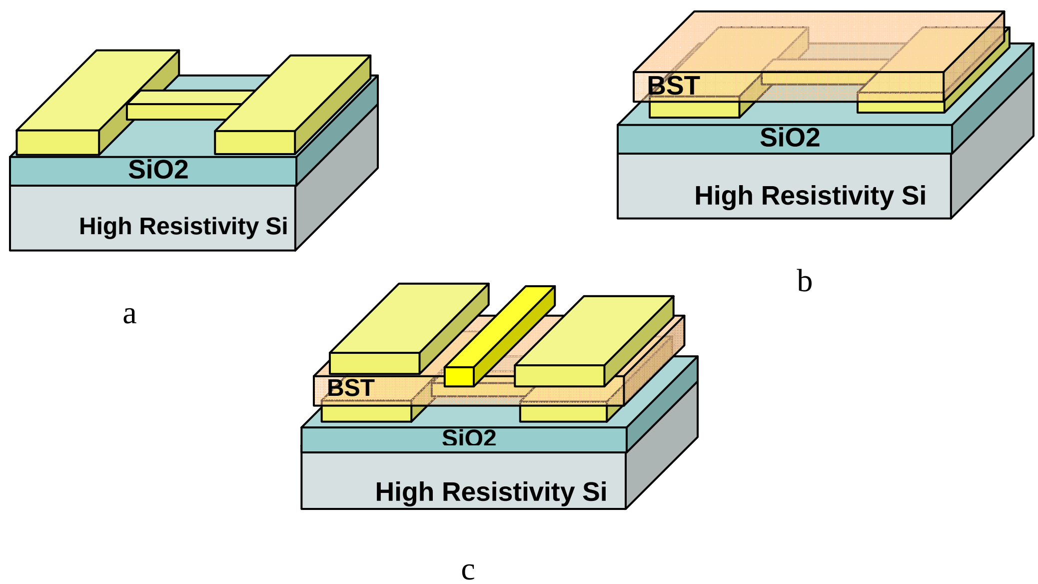

Figure 2. Fabrication Process for the Switch Outlined in Process Steps a through c
NOTE: Step a shows the metal1 pattern. Step b shows the entire sample coated with the BST thin-film, and step 3 the final device structure.

Note that the ground lines in metal2 and metal1 overlap to create a large capacitance in series with the small varactor capacitance resulting in the effective capacitance of the varactor. The shunt conductances of the large overlapping capacitance of the ground lines, as well as the varactor eliminates any need for via holes, resulting in a simple process. The important device parameters are (i) the varactor area (overlap area of the metal1 and metal2 layers), (ii) CPW transmission line parameters, such as the width of the center conductor, spacing between the center conductor and ground lines, and length of the CPW line sections, (iii) parasitic inductance and resistance of the thin-line shunting to ground in metal1, and (iv) the dielectric properties of the nano-structured BST thin-film. The varactor shunt switch can be precisely modeled as reported earlier [8, 9]. The larger area of the varactor results in a large zero-bias capacitance of the varactor. Devices can be designed for a specific frequency range of operation as the resonance frequency due to the series LC resonance of the varactor determines the maximum isolation of the switch. Large area varactors result in high isolation, at the same time, increasing the insertion loss of the switch. Ideally, one would like to reduce the varactor capacitance to the level of the line capacitance to obtain low insertion loss. This requirement is difficult to achieve in the case of large area varactors, as the dielectric tunability is limited to approximately 4:1 in our films [10]. Varactor shunt switches with different areas were designed with the dielectric tunability of 400% for the ferroelectric thin-films. Table 1 summarizes the designed devices, and the simulated performance of the switches. The electromagnetic simulations were carried out using Sonnet em tools. As one can see, the smaller the area of the varactor, lower the insertion loss of the switches.

Table 1. Simulated Performance Summary of the Switches Designed, Based on the Assumption of ε_{BST}=500, tanδ(BST)=0.047 at Zero-Bias and ε_{BST}=150 and tanδ(BST)=0.03 at 10 V bias

Device Area (μm^2)	**Resonance Frequency fr (GHz) for OFF state**	**Insertion Loss@fr (dB) (ON state)**	**Isolation @fr (dB) (OFF state)**
2.5 x 2.5	110	2.5	26
5 x 5	60	4	29
7.5 x 7.5	38	5	31
10 x 10	30	8	32
12.5 x 12.5	24	9.8	33
15 x 15	20	10	33

3. Experimental Results

The varactor shunt switch was tested using a HP8510 vector network analyzer and an on-wafer probe station. The voltage bias for the switch was applied using the VNA's bias tee, and an Agilent semiconductor parameter analyzer. The measurements were performed after a Line-Reflect-Reflect-Match (LRRM) calibration. The figure 3 shows the bias dependent S_{21} for a 15 x 5 μm^2 switch for bias voltages of 0 V and 9.5 V.

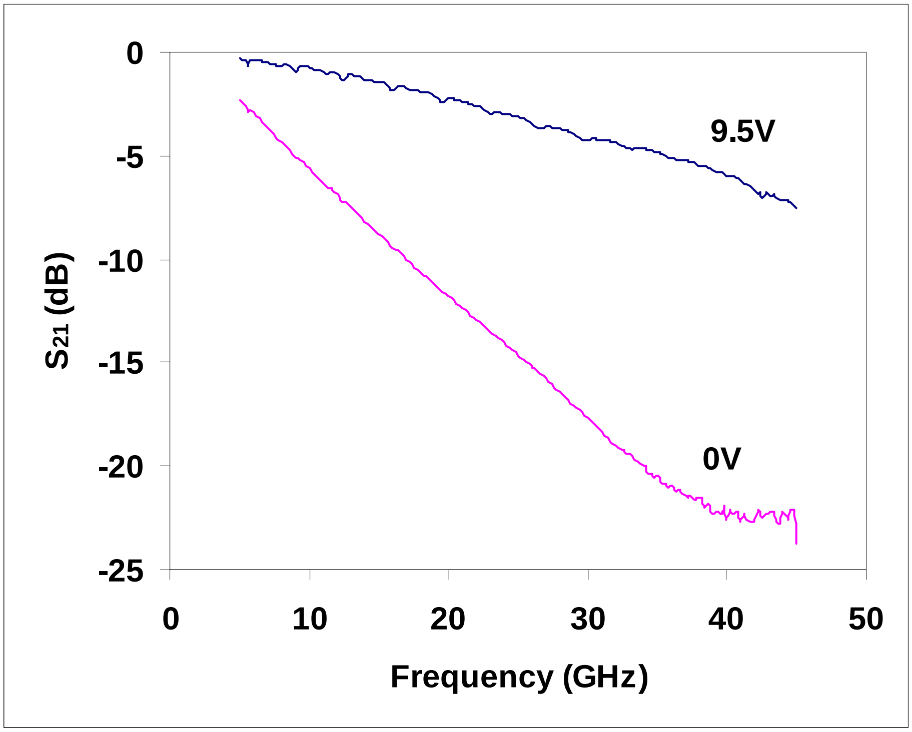

Figure 3. Bias-Dependent S21 as a Function of Frequency

The figure 4 shows the S_{11} for the same device for bias voltages of 0 V and 9.5 V. The device at zero-bias (OFF-state), showed an isolation of ~24 dB at the resonance frequency of 41 GHz. The insertion loss of the device at the highest bias voltage of 9.5 V was approximately 7 dB at 41 GHz.

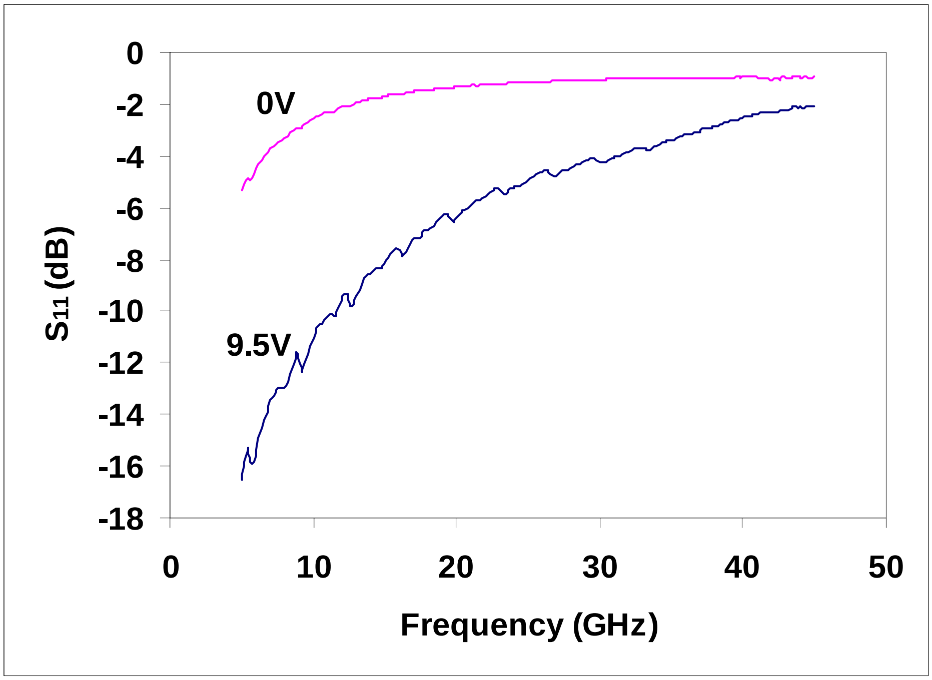

Figure 4. Bias-Dependent S11 as a Function of Frequency

Based on the experimental bias dependence of S_{21} and S_{11}, an electrical model was obtained for each bias voltage. The electrical model for the varactor allowed us to compute the dielectric properties of the BST thin-film as a function of frequency as well as voltage. Figure 5 shows the dielectric properties of the BST thin-film obtained at 20 GHz. As one can see, the dielectric tunability of the BST thin-film was more than 350%. The varactor capacitance was strongly frequency dependent assuming that the parasitic series inductance is constant over the frequency range of measurements. The dispersive behavior of the varactor capacitance could be potentially due to the nano-structured BST thin-film (60/40) being in ferroelectric region at room temperature.

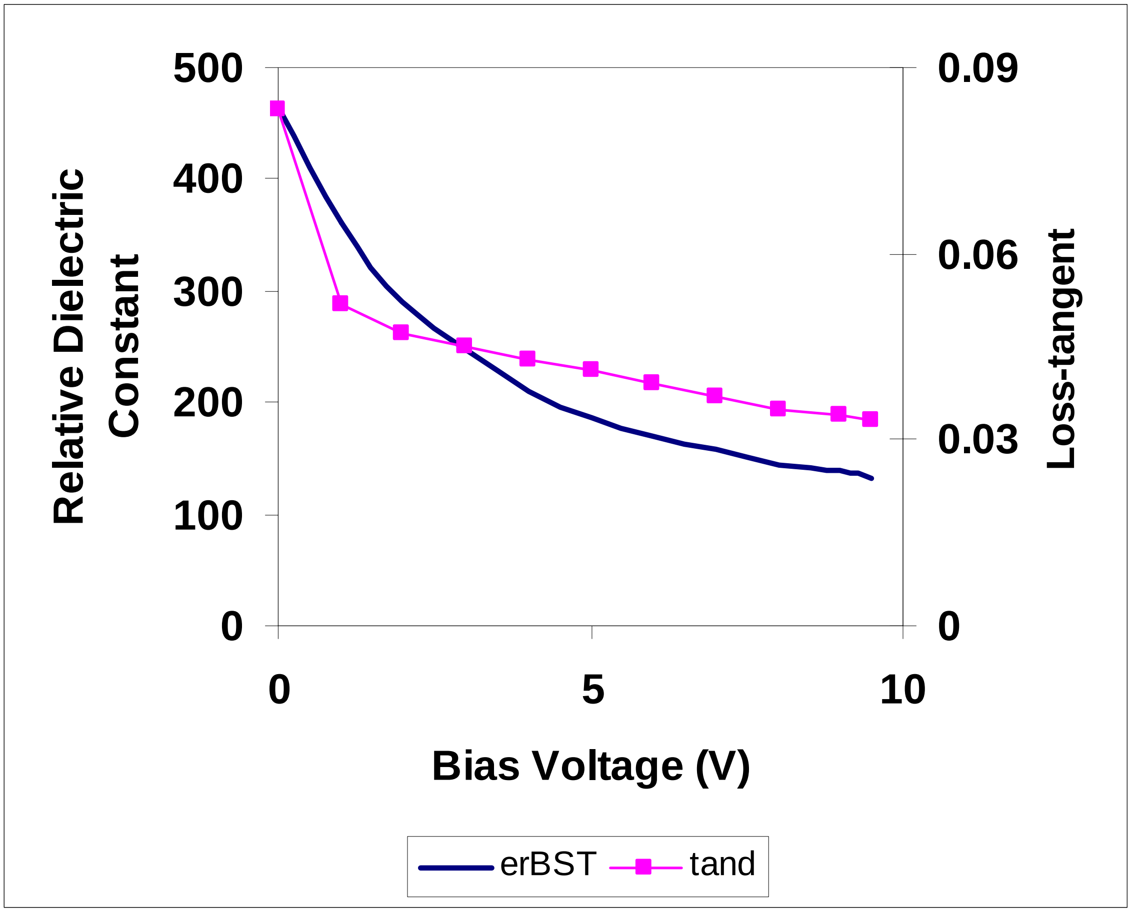

Figure 5. Dielectric Properties of the BST Thin-Film Extracted from the Measurements as a Function of Voltage at a Fixed Frequency of 20 GHz

Reported values for critical temperature (T_c) of BST(60/40) bulk ferroelectric is approximately 295 K[2]. The T_c in thin-film form of the BST thin-film could be higher due to various reasons such as the nanostructure, and modified ferroelectric properties in thin-films. By choosing a different composition of BST, such as BST(40/60), one can obtain paraelectric behavior and hence dispersion free capacitance vs frequency behavior at room temperature.

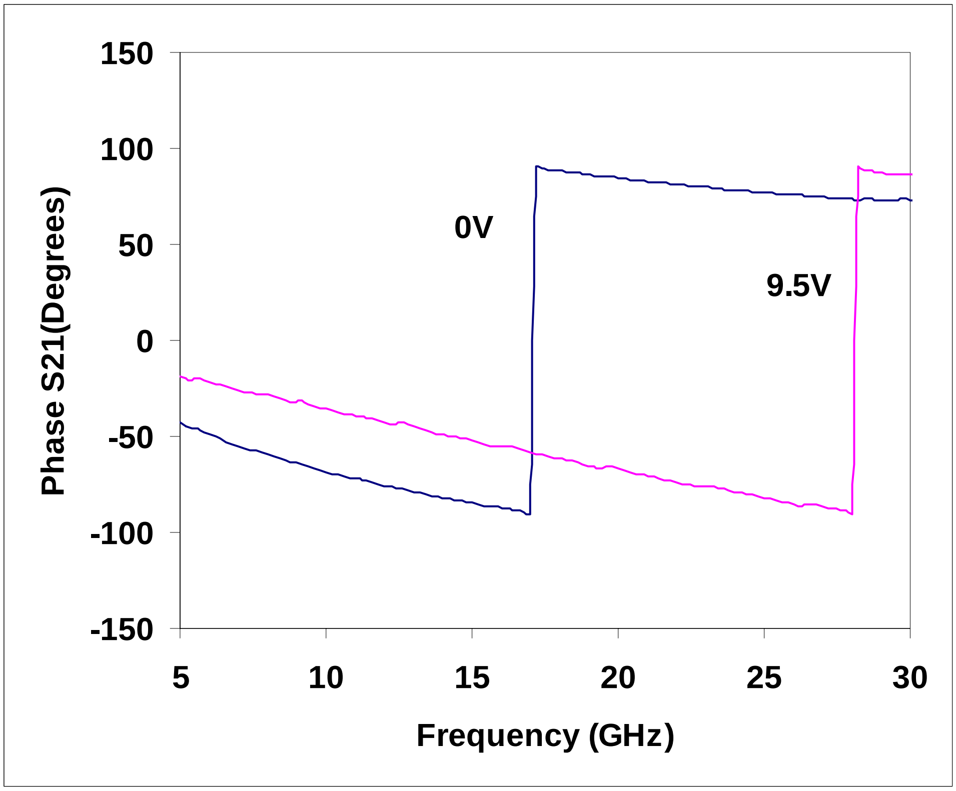

Figure 6. Phase of S21 versus Frequency for 0 V and 9.5 V

Figure 6 shows the phase of S_{21} as a function of the bias voltages for 0V and 9.5 V. The figure of merit for tunable phase shifters, relative phase shift per dB insertion loss was approximately 75 degrees per dB at 5 GHz, and drops down to 10 degrees/dB at 20 GHz. The drop in the figure of merit is also due to the dispersive nature of the varactor. Table 2 summarizes the potential applications of the varactor shunt switch for tunable/reconfigurable microwave and millimeterwave circuits.

Table 2

Application	Frequency Range	Implementation	Attributes
Switching Device	1-100 GHz	Shunt switch (CPW), Si MMIC compatible	Lower insertion loss for smaller devices
Circulator/Isolator	1-100 GHz	Shunt switch (CPW)	20-25 dB isolation
Phase Shifter	1-100 GHz	Periodic Loading	Analog, continuous, up to 75 deg/dB
Tunable filters	Microwave/millimeterwave	Periodic Loading	Low voltage tunable, CPW
Signal to Noise Enhancer	Microwave/Millimeterwave	Shunt Switch (CPW)	High power signals allowed to pass thru
Directed energy sensors	Microwave/millimeterwave, infrared, etc	Shunt switch (CPW)	Similar to SNE
Capacitive Sensors	Microwave	Shunt switch (CPW)	Resonance frequency shift
Piezo-electric sensors	Microwave	Shunt switch (CPW)	Piezoelectric PZT as ferroelectric film
IR sensors	Infrared	Shunt Switch	Resonance frequency shift

4. Conclusion

A Si MMIC compatible ferroelectric varactor shunt switch was presented for microwave/ millimeterwave tunable/reconfigurable circuits. The normally OFF varactor shunt switch is a simple device when compared with the RF MEMS shunt switches. The shunt switch is turned ON by the application of a dc bias which reduces the loading varactor capacitance to a minimum. The potential applications of the varactor shunt switch includes microwave/millimeterwave switches, circulators, tunable/reconfigurable filters, continuous analog phase shifters, and wireless sensors using the large capacitance change in the varactor.

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